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A Review of Research on Flexible Actuated Bionic Robots

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Abstract. Conventional rigid robots have significant shortcomings in complex environments, human interaction, and flexible manipulation. Inspired by organisms in nature, flexible-driven bionic humanoid robots have gradually emerged. Leveraging their soft and agile characteristics, they can better adapt to different scenarios and have become a research focus in the field of robotics. Examples include drive technology, motion control methods, and their practical applications in medical rehabilitation, industrial operations, and disaster relief. This paper finds that although research on flexible-driven bionic humanoid robots has yielded good results in many fields, challenges remain in drive efficiency and control precision. Currently, technological development is continuously driving the progress of robotics technology, and flexible-driven bionic robots have broad development potential in the future. To enable them to play a greater role in more scenarios, researchers need to continuously overcome existing challenges. This paper provides a foundation for understanding the development of this field and conducting related explorations.

Keywords: flexible actuation, bionic robot, motion control, soft robot, application scenarios

1. Introduction

Over the past few decades, conventional rigid robotic arms have played a key role in fields such as factory manufacturing. However, their rigid structure makes them difficult to adapt to complex scenarios and cannot safely interact with humans. They are also prone to damage when handling fragile or irregularly shaped objects [1]. In contrast, creatures in nature, such as earthworms and octopuses, can adapt to various environments and perform complex actions with their flexible bodies and muscles. This has inspired researchers. Flexible-driven bionic robotic arms are designed based on the characteristics of these creatures. They integrate the knowledge of bionics, materials science and robotics. In creating robotic arms that are as flexible and adaptable as living organisms, the emergence of flexible-driven bionic robots has opened up new ways to solve the limitations of traditional rigid robots. They are expected to show unique advantages in more fields and promote the further development of robot technology.

Many experts have explored flexible driven bionic robots. Tolley, et al. have summarized the design, manufacturing and control methods of flexible robots in detail and sorted out the key research results in this field [1]. Trivedi, et al. examined the bio-inspiration of flexible robots, the current research status and the problems that will be encountered in the future, suggesting that flexible robots have great application prospects in complex environments [2]. Yasa, et al. have

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further summarized the driving mode, modeling method and control strategy of flexible robots, providing a clear picture of the current research landscape [3]. Collectively, it can be seen that flexible driven bionic robots have an indispensable position in the future development of science and technology, and their application scope is expected to expand, bringing new changes to many fields.

Based on this, this paper uses the literature review method to summarize the core technologies of motion control of flexible driven bionic robots, analyze its typical application scenarios, and also discuss the current problems. This paper aims to make predictions for the development of this field and provide reference for researchers to further study and understand this field.

2. Overview of key technologies

The reason why agile driven bionic robots can move as flexibly as living organisms is that their agile driving mode and corresponding motion control technology are key. According to the difference in driving principle, the current mainstream agile driving mode is mainly divided into four categories: pneumatic/hydraulic drive, intelligent material drive, rope drive and antagonistic bionic muscle drive [4]. These driving methods have their own characteristics, and their synergistic effect allows bionic robots to exhibit motion characteristics that are closer to living organisms in different scenarios.

Currently, the most advanced methods are pneumatic and hydraulic drives. These utilize the pressure of gas or liquid to deform flexible structures, thereby driving the robot. This drive method boasts advantages in flexibility and strength, and is commonly used in flexible robotic arms and wearable machines. Smart material drives utilize special materials that deform under external stimuli (such as temperature and voltage), such as shape memory alloys (SMA), enabling miniaturized designs. However, their strength and reaction speed still need improvement. Rope drives simulate the muscles and tendons of living organisms, using flexible cables to move the robot. This is suitable for creating robots that can flexibly extend, retract, and bend like an elephant's trunk. Antagonistic bionic muscle drives mimic the operating mode of biological muscles, using two sets of actuators to apply opposing forces, achieving flexible robot movements and stiffness adjustments. From an application perspective, different drive methods each have their own advantages. In future robot development, they will all play unique and important roles, continuously pushing robot technology to new heights.

Given that the body of a flexible robot is flexible and has infinite motion angles, the traditional control methods for rigid robots are no longer applicable. The current control methods are mainly divided into two categories: model control and model-free control [5]. Model control is to build a motion model of the robot and plan the control method according to the model, which can achieve a high degree of control accuracy. Model-free control does not require the construction of a precise model, and improves the motion mode by the interaction between the robot and the environment, which is more suitable for complex unknown environments [6]. In practical applications, appropriate control methods should be flexibly selected for different scenarios in order to maximize the efficiency of flexible robots and better adapt to various complex and changing working environments.

3. Typical application scenarios

With the continuous progress of science and technology, flexible drive bionic robots have been used in many fields. In many situations where traditional rigid robots are unable to perform their tasks,

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they have shown unique advantages. With their unique design, these robots can work flexibly in complex environments, bringing new possibilities to industrial production and scientific research.

3.1. Medical rehabilitation field

In the field of medical rehabilitation, the flexibility and safety of flexible robots are extremely significant. They can assist stroke patients in carrying out rehabilitation training without causing secondary damage to the patient's body. In complex medical scenarios, their unique performance can also provide patients with more considerate and gentle rehabilitation support, helping patients to recover their health better.

The flexible rehabilitation glove developed by the University of Science and Technology of China imitates the deformable characteristics of human fingers and can assist patients in performing daily actions such as combing hair, brushing teeth and writing. Clinical tests show that after using this glove for rehabilitation training, patients' fine motor skills of the hands are significantly improved and they can complete daily activities that they could not do before [7]. There is also a BEAR-H1 lower limb exoskeleton robot, which adopts a flexible drive mode and can provide walking assistance to patients with lower limb movement difficulties. It uses sensors to detect the patient's movement intention and adjusts the assistance intensity in time to effectively enhance the effectiveness of rehabilitation training [8]. With the help of modern technology, these advanced devices continue to bring new hope to patients, improve their quality of life, and promote rehabilitation medicine to a new level.

The elephant trunk robot developed by Dalian University of Technology has also been successfully applied to assist stroke patients. It can achieve soft and hard switching and help patients complete actions such as picking up items and opening cabinets, further expanding the application field of flexible robots in the field of medical rehabilitation [9]. However, its application scenarios can be further explored, such as playing a role in more scenarios such as postoperative recovery.

3.2. Industrial flexible operation field

In industrial manufacturing, conventional rigid robotic arms are likely to cause damage when dealing with fragile and irregularly shaped workpieces, and are not easy to adapt to complex production environments. Flexible driven bionic robots, relying on their soft and flexible characteristics, have effectively solved this problem and have been widely used in scenarios such as workpiece grasping and parts assembly [10]. Compared with traditional rigid robotic arms, flexible driven bionic robots have obvious advantages in industrial production, can better meet diverse production needs, and inject new vitality into the development of modern industry.

The flexible grinding robot developed by Shanghai Jiaotong University is used for grinding complex curved surface workpieces such as aero-engine blades. It achieves fitting grinding by means of flexible drive, which not only improves the grinding accuracy but also ensures the surface quality [11]. Data shows that the octopus-tentacle-like flexible robotic arm introduced by Foxconn Technology Group uses rope drive and can be flexibly bent and extended. It can adaptively grasp electronic components of different shapes and sizes, avoiding the squeezing damage when grasped by rigid robotic arms, and improving the assembly efficiency. The grasping qualification rate of this flexible robotic arm reaches 99.2%, and the assembly efficiency is more than 30% higher than that of traditional rigid robotic arms [12]. The flexible robotic arm and the flexible grinding robot play important roles in their respective fields. With their unique performance, they bring significant advantages to manufacturing and promote the development and progress of related industries.

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3.3. Confined space detection and rescue

In confined space situations such as post-earthquake rescue and pipeline exploration, conventional rigid robots, constrained by size and rigidity, find it extremely difficult to enter complex gaps to carry out their work. Flexible-driven bionic robots, however, relying on their ability to continuously deform, can nimbly traverse confined spaces to accomplish important missions such as detection and rescue. This unique advantage of flexible-driven bionic robots can play a significant role in many special scenarios, providing new approaches and methods for solving practical problems.

The earthworm-like flexible rescue robot developed by the Institute of Automation of the Chinese Academy of Sciences uses a pneumatic drive mode. Its body can continuously extend, retract and bend, and it can pass through the tiny gaps in the building ruins. Its infrared sensors and cameras can transmit images and temperature information inside the ruins in real time, helping rescuers to find survivors [13]. In a building collapse accident in a certain region in 2024, this robot successfully entered the ruins and located the three survivors, winning valuable time for the rescue operation [14]. The flexible pipeline inspection robot developed by China University of Petroleum can adapt to oil and gas pipelines of different diameters. Using flexible drive, it moves and turns within the pipeline, accurately identifying defects such as cracks and corrosion, achieving a detection accuracy of 98.5%, significantly reducing the cost and risk of manual inspection.

4. Existing problems and challenges

Although flexible-driven bionic robots have achieved certain results, they still face some problems and challenges due to constraints such as materials and control processes.

Current driving methods are difficult to achieve the requirements of strong power, fast response, small size and long endurance at the same time. First, the driving efficiency is still lacking. Pneumatic/hydraulic driving relies on external air and hydraulic sources, which restricts the robot's range of motion. The response speed of smart material driving is slow and the service life is relatively short. The cables of rope driving are prone to wear and tear and are more complicated to operate, affecting the stability of the robot's movement [15]. In actual application scenarios, the limitations of these driving methods will be further highlighted, bringing many challenges to the widespread application of robots.

It is also difficult to achieve both control accuracy and response rate. The body of flexible robots is soft and has many angles of movement, making it difficult to build accurate motion models [16]. Although the control methods based on models have high accuracy, they are complicated to calculate and have a slow response rate. Model-free control methods have a fast response, but poor accuracy. It is difficult to ensure the stability of motion in complex environments. The performance requirements of flexible robots are different under different working conditions, which further exacerbates the difficulty of balancing accuracy and speed.

In addition, there is still room for improvement in engineering level and material performance. The flexible materials used in flexible robots have poor strength and are prone to aging, making them difficult to adapt to complex rescue and industrial environments [17]. The miniaturization and integration of flexible robots are also not ideal, the manufacturing cost is high, and large-scale application is difficult to achieve. In the long run, only by continuously overcoming these problems can flexible robots play a greater role in more fields.

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5. Conclusion

This article analyzes the key technologies, common application scenarios, and current challenges and difficulties of motion control for flexible driven biomimetic robots. The following conclusions are drawn. Flexible driven biomimetic robots, with their soft, agile, and stable characteristics, have broken the constraints of traditional rigid robots. They have broad application potential in medical care, industrial operations, narrow space detection and rescue, and other fields. The mainstream flexible driving methods currently have their own advantages and disadvantages, and motion control methods are moving towards precision and efficiency, with a focus on balancing control accuracy and response speed. However, there are still many challenges in driving efficiency, control precision, perception feedback, material performance, etc. Further exploration and innovation are needed to enhance the overall performance of robots, thus better adapting to more complex and ever-changing practical scenarios.

However, this research has some significant shortcomings. First, the literature review does not comprehensively cover earlier classic studies. Second, it lacks actual experimental verification and specific data support. Third, the discussion on the industrial application of flexible-driven bionic robots is relatively brief, without in-depth analysis of the challenges of large-scale application. Future research can expand the scope of literature review and balance early classic exploration with the latest research achievements. Simple simulation experiments are also needed to analyze the effects of different driving modes and control policies. It is necessary to deeply understand the difficulties in the industrialization of flexible robots, provide simple solutions, and further optimize relevant strategies based on practical application scenarios to better promote the development of the flexible robot industry.

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